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Effects of Inboard Horizontal Field of View Display Limitations on Pilot Path Control During Total In-Flight Simulator (TIFS) Flight Test

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Abstract

A flight test was conducted aboard Calspan's Total In-Flight Simulator (TIFS) aircraft by researchers within the eXternal Visibility System (XVS) element of the High-Speed Research program. The purpose was to investigate the effects of inboard horizontal field of view (FOV) display limitations on pilot path control and to learn about the TIFS capabilities and limitations for possible use in future XVS flight tests. The TIFS cockpit windows were masked to represent the front XVS display area and the High-Speed Civil Transport side windows, as viewed by the pilot. Masking limited the forward FOV to 40° horizontal and 50° vertical for the basic flight condition, with an increase of 10° horizontal in the inboard direction for the increased FOV flight condition. Two right-hand approach tasks (base-downwind-final) with a left crosswind on final were performed by three pilots using visual flight rules at Niagara Falls Airport. Each of the two tasks had three replicates for both horizontal FOV conditions, resulting in twelve approaches per test subject. Limited objective data showed that an increase of inboard FOV had no effect (deficiencies in objective data measurement capabilitites were noted). However, subjective results showed that a 50° FOV was preferred over the 40° FOV.

Summary

Researchers within the eXternal Visibility System (XVS) element of the High-Speed Research (HSR) program are developing and evaluating information display concepts that will provide the flight crew of the proposed High-Speed Civil Transport (HSCT) with integrated imagery and symbology to permit required path control and hazard avoidance functions while maintaining required situational awareness. The purpose of this research was to investigate the effects of inboard horizontal field of view (FOV) display limitations on pilot path control and to assess the Total In-Flight Simulator (TIFS) in-flight simulation capability for possible use in future flight tests. The assessment was conducted as part of the HSR flight deck XVS flight test activity aboard Calspan's TIFS aircraft. The effects on pilot path control when using 40° and 50° horizontal FOV on the front windscreen (10° inboard increase) of the TIFS aircraft were studied by masking the cockpit windows to represent the front XVS display area and the HSCT side windows as viewed from the pilot eye reference point. Masking limited the forward FOV to 40° horizontal and 50° vertical for the basic flight condition, with an increase of 10° horizontal in the inboard direction for the increased FOV flight condition.

Two right-hand approach tasks (base-downwind-final) with a left crosswind on final were performed by three pilots using visual flight rules at Niagara Falls Airport. The first task was a follow-me approach using a Beechcraft Be-200 as a lead aircraft and the second task was a TIFS-aircraft-only approach. The Be-200 lead aircraft represented a typical airplane flying in the pattern. Each of the two tasks had three replicates for both horizontal FOV conditions, resulting in twelve approaches per test subject.

The limited amount of objective data from the experiment showed that an increase of inboard FOV had no effect during either turn to base or turn to final on the maximum bank angle achieved or on the average bank angle attained. Similarly, no FOV effects were found for the touchdown performance measures of threshold altitude, distance from threshold, or maximum touchdown sink rate.

Statistical analysis of subjective questionnaire results indicates that no significant differences were found among FOV's for assessment of (1) the usability of the forward display configuration for flying straight and level on the different flight segments, (2) turn initiation and rollout, (3) achieving lateral ground track alignment, (4) maintaining path on final with a left crosswind, (5) following the Be-200, (6) flying the inertial ground track by out-the-window cues, or (7) controlling landing flare. However, subjective results showed that the 50° FOV was preferred over the 40° FOV for following the Be-200 general aviation aircraft, flying the entire landing approach (downwind-base-final), and acquiring the runway and/or target after rolling out on final approach. The pilots felt that FOV had no effect on pilot path control with the left crosswind on final, either during straight and level flight or during landing flare. Being accurate to only 100 m, the global positioning system (GPS)/inertial navigation system (INS) equipment currently used aboard the TIFS aircraft was insufficient for objective performance data collection. Differential GPS is needed aboard the TIFS aircraft to accurately measure ground track to the precision desired in future XVS flight tests.

Introduction

As part of the High-Speed Research (HSR) program, researchers within the Flight Deck Systems (FDS) technology area are tasked to develop and demonstrate operationally viable, economically feasible, and potentially certifiable eXternal Visibility System (XVS) concepts that would permit a no-nose-droop configuration of a High-Speed Civil Transport (HSCT) and expanded low-visibility HSCT operational capabilities. (Planning for the XVS is described in the *Planning and Control Document for January 1996 to December 1998—4.1.1 External Visibility System (XVS),* prepared by the Boeing Commercial Airplane Group, 1996. Unpublished.)

The nose-droop mechanism currently used in the British-French Concorde provides the forward visibility required by the flight crew to adequately see the runway during landing and takeoff. The equipment needed to lower and raise the Concorde's nose adds weight, and the nose in the lowered (or drooped) position adds drag.

To be operationally viable, the HSCT design must be optimized to minimize weight and aerodynamic drag. The weight penalty of a nose-droop configuration for an aircraft the size of an HSCT is roughly estimated to be 10 000 pounds takeoff gross weight. An external visibility system that would provide a capability equivalent to the forward facing windows in current commercial transport aircraft would eliminate the need for a hydraulic-powered mechanical nose on the HSCT and avoid the weight penalty associated with the nose-droop mechanism. The XVS concept need not provide a direct visual replacement for the forward windows, but must enable the flight crew to perform the required functions of path guidance and hazard avoidance at the same levels provided by forward facing windows. (The HSCT requirements appear in the *HSR Flight Deck External Vision System (XVS) Requirements, Concepts/Approaches, Display Interface Requirements, and Technology Readiness Studies—Volume II: Candidate Concepts Definition,* prepared by the Boeing Commercial Airplane Group. Final Report April 25, 1995. Unpublished.)

The XVS will consist of a suite of sensors and supporting systems that will provide information normally available to the flight crew in a conventional cockpit through pilot vision in the forward direction. The initial assumption by the XVS element of the FDS program was that the XVS, in combination with any conventional side windows, would provide each pilot with a FOV at least as great as the guidelines specified in ARP4101/2. (See ref. 1 and appendix A.) To satisfy the criteria of the ARP4101/2 vision envelope, the pilot display configuration contained in the FDS benchmark consists of one XVS display each for the pilot and copilot, each containing 40° horizontal and 50° vertical FOV. The forward visibility provided by the XVS display is augmented by natural vision through the side windows. (The HSCT configuration is described in the *High Speed Civil Transport (HSCT) Technology Concept Airplane Configuration Description Document—Task 2.1: Technology Integration*, prepared by the Boeing Commercial Airplane Group. April 1, 1996. Unpublished.)

Researchers conducted a flight test to examine the effects of varying the horizontal inboard FOV available to the pilot. The primary objective of this investigation was to test the hypothesis that increases in the XVS inboard FOV provide the pilot with better roll information (more horizon visible for roll cues) and aid the pilot in crosswind landings (more runway visible in crabbed landing position). The inboard FOV criterion is one of the many high-priority research issues under investigation. (See ref. 2.) A secondary objective was to learn about the Total In-Flight Simulator (TIFS) in-flight simulation capabilities and limitations for possible use in future flight tests by the XVS element of the HSR FDS program. Flying tasks were chosen that required viewing the inboard edge of the FOV, such as following traffic in a right-hand visual flight rules (VFR) pattern and approaches containing a left crosswind on final.

Abbreviations

AGL	above ground level
ANOVA	analysis of variance
C-H	Cooper-Harper
EP	evaluation pilot
F	F ratio
FDS	Flight Deck Systems
FOV	field of view
GPS	global positioning system
HFOV	horizontal field of view
HSCT	High-Speed Civil Transport
HSR	High-Speed Research
HUD	heads-up display
INS	inertial navigation system
PERP	pilot eye reference point
prob.	probability
TIFS	Total In-Flight Simulator
VFR	visual flight rules
VMS	Visual Motion Simulator
XVS	eXternal Visibility System

Test Overview

Evaluation Pilots

Three test pilots (one from McDonnell Douglas Aerospace, two from NASA Langley Research Center) served as evaluation pilots (EP) during the 2 days of flight testing. Subjects were asked to complete a brief questionnaire describing their flight experience. All three pilots had experience flying commercial and military aircraft. The number of years flying commercial aircraft ranged from 11 to 25, with a mean of 19.7 years. The number of years flying military aircraft ranged from 10 to 16, with a mean of 14 years. The total number of hours flying as pilot in command ranged from a low of 4000 hours to a high of 7000 hours, with a mean of 5666.7 hours. All pilots were thoroughly briefed on TIFS egress, normal procedures, and emergency procedures prior to their first flight.

Test Environment

The inboard FOV flight tests were conducted over a 2-day period at Niagara Falls International Airport, Niagara Falls, New York. These tests were conducted in an airport terminal area with other terminal area traffic. Flight conditions were VFR and minimal turbulence.

Test Aircraft

Two aircrafts were used for these tests. The first aircraft was Calspan's TIFS aircraft, used as the test aircraft for all trials. (See fig. 1.) The TIFS aircraft is an NC-131H modified to be a six-degree-of-freedom in-flight simulator. (See refs. 3 and 4.) The TIFS model-following control utilizes elevator, aileron, rudder, throttle, direct-lift flaps, and side-force surfaces to produce motions that duplicate the computed responses of the simulated aircraft. The second aircraft, a Beechcraft Be-200 general aviation aircraft, was used as a target during specific portions of the flight test.

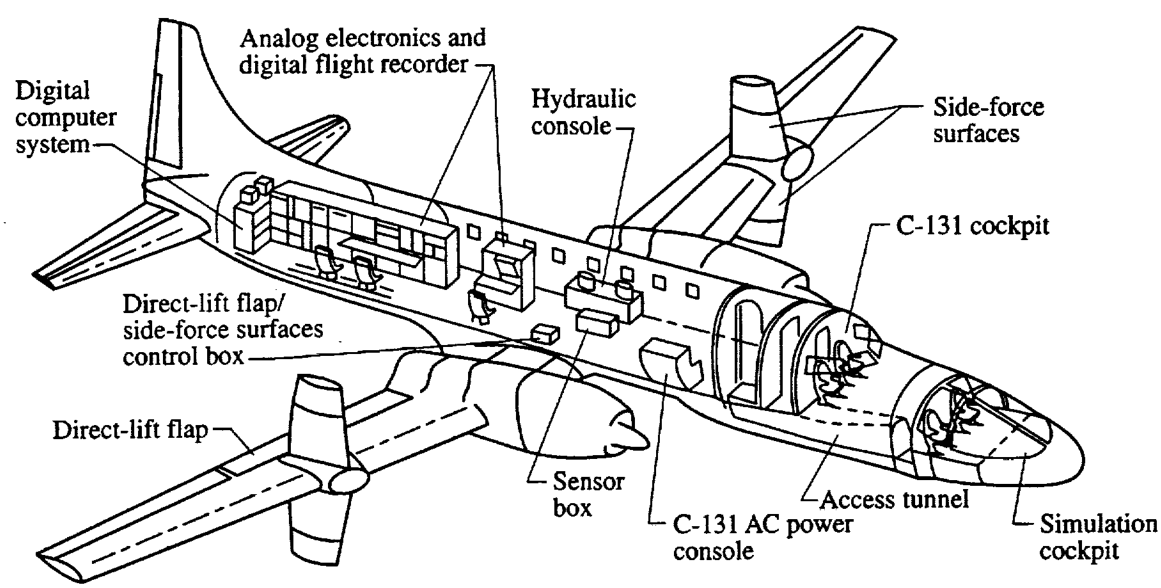


Figure 1. Schematic of TIFS aircraft.

The flight crew on the TIFS aircraft consisted of two Calspan safety pilots, two Calspan engineering personnel, two EP's, and one test engineer. Since the NC-131H aircraft and the HSCT Reference H configuration (simulated aircraft) have vastly different dimensions, the approach and landing simulation task was flown to a simulated aircraft wheel touchdown. The EP was approximately 45 ft above ground level (AGL) at simulated gear touchdown. (See fig. 2.) The experimental run ended once the EP heard a simulated "tire screech" of the HSCT's landing gear.

Controls and Displays

The EP occupied the left seat in the TIFS simulation cockpit and the test engineer occupied an observer seat on the right. The EP utilized a wheel and column controller for pitch and roll control and rudder pedals for yaw control. For this flight experiment, the XVS display was represented by the real world as viewed through the TIFS F/A-18 heads-up display (HUD). Cockpit windows were masked to represent the front XVS display area and the HSCT side windows as viewed from the pilot eye reference point (PERP). This masking limited the forward FOV to 40° horizontal and 50° vertical for the basic condition, with an increase of 10° horizontal in the inboard direction for the increased FOV condition. (See fig. 3.) Head movement by the EP could effectively increase the total FOV for the representative XVS display since masked cockpit windows, instead of an actual XVS display, were used in this flight test. To mitigate XVS display differences between TIFS and the HSCT configuration, the EP was instructed to keep his head positioned at the PERP.

For each run, a minimum symbology set was present on the 20° FOV HUD that served as the pilot's primary flight display. (See fig. 4.) The symbology for the flight director commands and flare cue were removed from the HUD for this flight test, forcing the pilot to control the aircraft from visual cues. Engine gauges, flap gauges, and a landing gear selector were located on the instrument panel. Thrust control was provided through a throttle quadrant located on a center-mounted console. All XVS display evaluation runs were flown with autothrottles engaged. The EP was responsible for overriding or disengaging the autothrottles to reduce thrust (if necessary) for landing.

Instrumentation

The TIFS aircraft is equipped with an Ampex AR700 airborne digital recorder. Sixty analog channels of data elements are recorded at 100 samples per second with twelve bit resolution. The TIFS aircraft data recorded during the test runs are listed in appendix B.

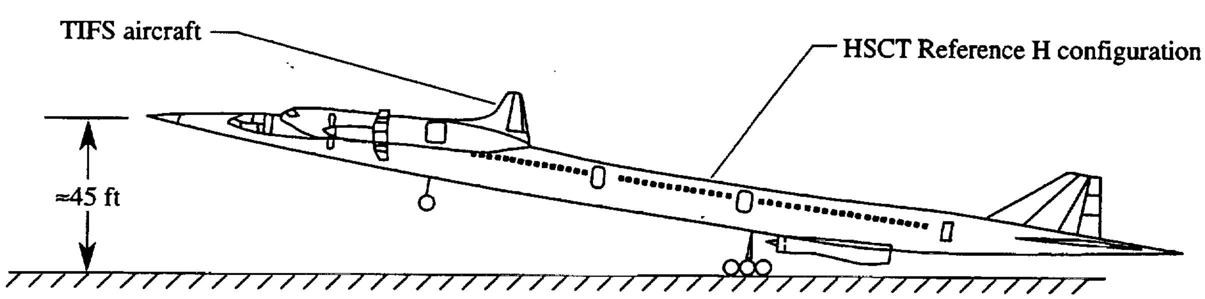
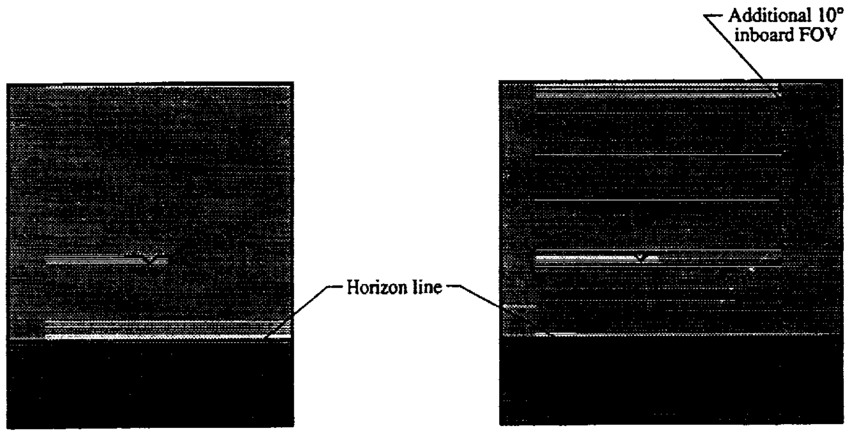


Figure 2. Sideview of TIFS simulation of HSCT Reference H configuration.



(a) 40° horizontal by 50° vertical. (b) 50° horizontal by 50° vertical.

Figure 3. The XVS display forward FOV's.

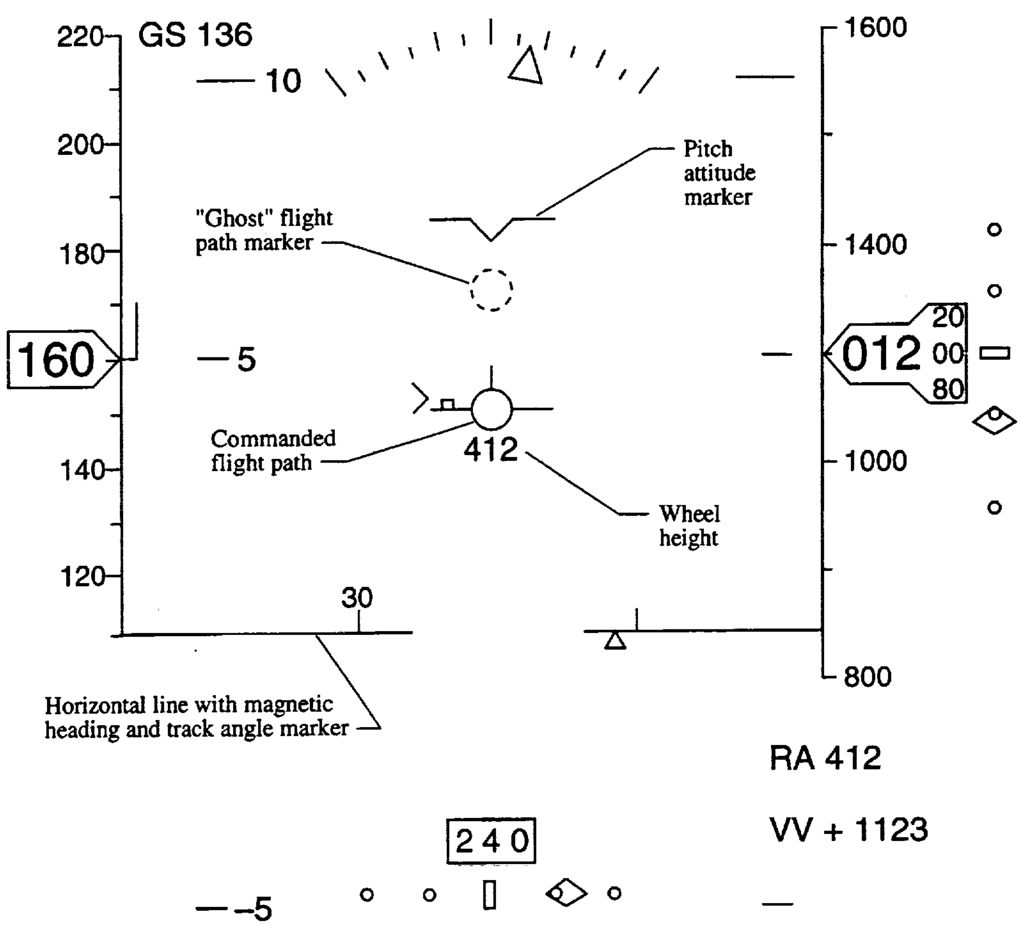


Figure 4. Minimum symbology set on TIFS F/A-18 HUD.

The TIFS aircraft is equipped with video cameras to record an over-the-shoulder view of the EP and the forward visual scene. A monochromatic camera was installed to record the HUD presentation and the forward, outside visual scene. This video information was presented to the safety cockpit and engineering stations in the TIFS cabin area. The video recorders also recorded onboard audio communications.

Experiment Design and Procedure

This study was a 2 × 3 × 3 (40°, 50° FOV × Test subjects × Task replications) factorial design, with trials blocked by FOV. Two right-hand VFR approach tasks with a left crosswind on final were performed by three pilots at Niagara Falls Airport (fig. 5). Each of the two tasks had three replicates for both horizontal FOV conditions, resulting in twelve approaches per test subject. (See table 1.)

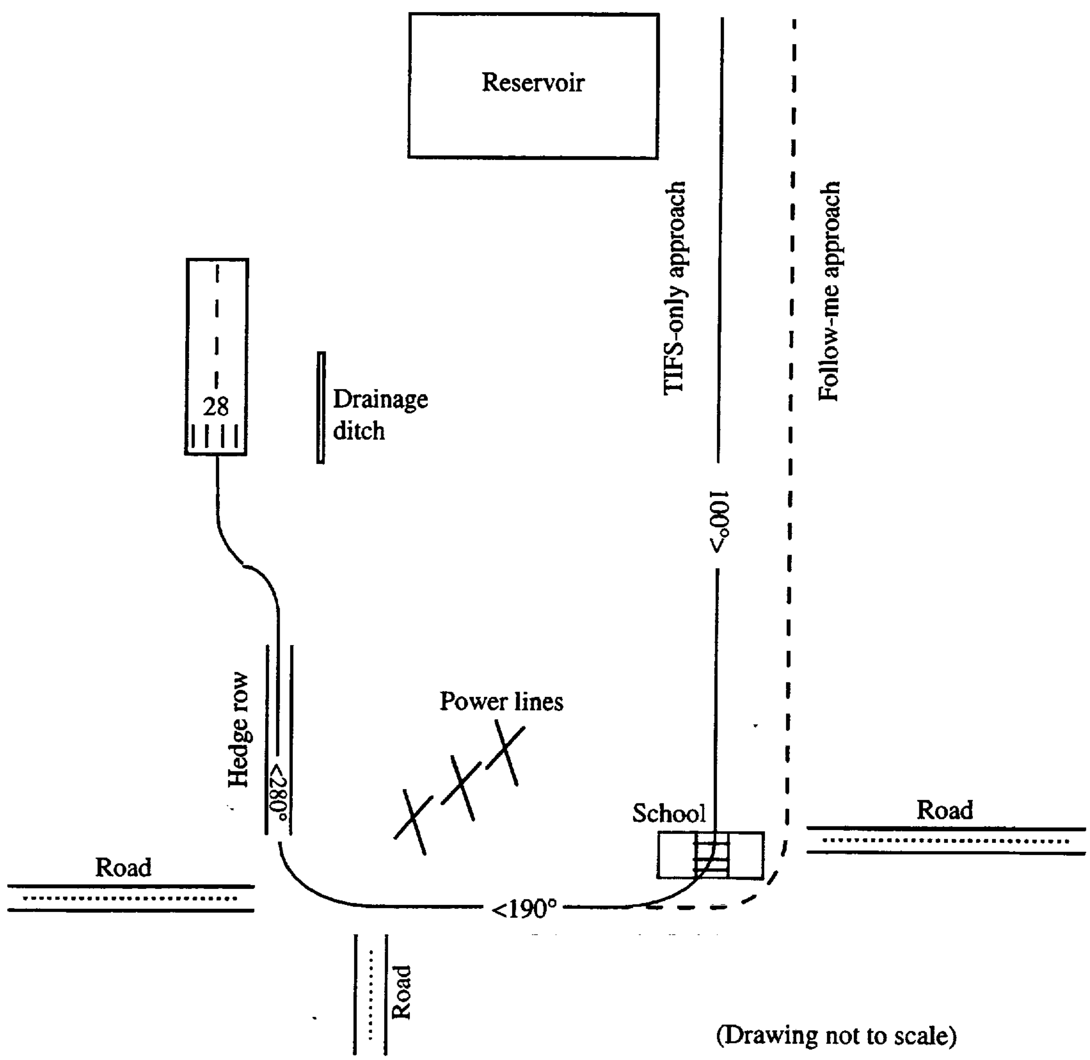


Figure 5. Right-hand VFR approaches flown at Niagara Falls Airport.

Table 1. Summary of Pilot Trials

Approach Number	FOV	Follow traffic	TIFS only	Questionnaire completed
1	40	✓		
2	40	✓		
3	40	✓		✓
4	40		✓	
5	40		✓	
6	40		✓	✓
7	50	✓		
8	50	✓		
9	50	✓		✓
10	50		✓	
11	50		✓	
12	50		✓	✓

Flying task one required the TIFS EP to follow the Be-200 lead aircraft on approach (downwind-base-final) to landing. The Be-200 lead aircraft represented a typical airplane flying in the pattern. The EP was instructed to maintain a 2-nmi separation between the TIFS aircraft and the Be-200. Flying task two required the TIFS EP to use geographical references to fly the approach (downwind-base-final) to landing. Note that each task was a right-hand VFR approach with data acquisition beginning on the downwind leg.

At the start of each approach, the TIFS aircraft was

Trimmed, wings level, gear down
Oriented parallel to the runway
At 159 knots (towards the runway area)
At approach flap settings
Positioned approximately abeam of the threshold
At an altitude of 1000 ft above the ground
Positioned approximately 2 nmi behind the Be-200 (when appropriate)

For all trials, the final approach consisted of a 300-ft lateral offset to the right of the runway, with a correction to line up with the runway on short final upon hearing an automated TIFS cockpit voice saying "correct." The offset landing task was used to increase the workload and direct involvement of the pilot in the manual control task during the final stages of the landing. There was also a simulated 10-knot left crosswind on final, created by the TIFS modeling capability, for all approaches. The design of these two approach tasks (follow-me, TIFS-only) required the pilot to view the inboard edge of the FOV in the XVS display.

For both approach tasks, each pilot was asked to complete a questionnaire (appendix C) after flying the third replicate for each FOV condition. (See table 1.) The intent of the questionnaire was to identify possible effects on pilot path control when increasing the inboard horizontal FOV of the forward display by 10°.

Each of three test pilots flew the matrix of approaches described in table 1. Because of the dynamic flight testing environment, approaches were not flown in order. The actual approach test matrix flown is shown in table 2. Note that pilot 2 only completed two of three TIFS-only runs for the 40° FOV, because of fuel limitations of the TIFS aircraft.

Table 2. Flight Test Run Matrix

Run number	Pilot	FOV	Follow traffic	TIFS only
1	1	40		✓
2	1	40		✓
3	1	40		✓
4	1	50		✓
5	1	50		✓
6	1	50		✓
7	2	50		✓
8	2	50		✓
9	2	50		✓
10	3	50		✓
11	3	50		✓
12	3	50		✓
13	3	50	✓	
14	3	50	✓	
15	3	50	✓	
16	3	40	✓	
17	3	40	✓	
18	3	40	✓	
19	3	40		✓
20	3	40		✓
21	3	40		✓
22	2	40		✓
23	2	40		✓
24	2	50	✓	
25	2	50	✓	
26	2	50	✓	
27	2	40	✓	
28	2	40	✓	
29	2	40	✓	
30	1	40	✓	
31	1	40	✓	
32	1	50	✓	
33	1	50	✓	
34	1	50	✓	
35	1	40	✓	

Performance Metrics

Both objective and subjective data were collected to determine possible inboard FOV effects on pilot path control and landing performance.

Path Control Metrics

The objective metrics used to assess a pilot's ability to maintain path control were roll control performance data (maximum bank angle, average bank angle) and time to acquire a stable path after turns.

The subjective metrics used to evaluate a pilot's ability to maintain path control were pilot comments and questionnaire ratings. In the questionnaire, the EP rated the effort required to use the forward display configuration (40° or 50° horizontal FOV) for the following:

Flying straight and level on the different flight segments
Turn initiation and rollout
Achieving lateral ground track alignment
Maintaining path on final with a left crosswind
Following the Be-200 general aviation aircraft (where applicable)
Flying the inertial ground track by the out-the-window cues
Landing flare

Touchdown Metrics

The objective touchdown metrics used were dispersion footprint, sink rate, and threshold altitude.

The subjective touchdown metric was a modified Cooper-Harper (C-H) rating (fig. 6) assigned by each pilot for the landing phase of flight for both horizontal FOV (40° or 50°) conditions. Figure 7 shows the flight card used by pilots to assign their modified C-H rating. Each rating is based on a series of three runs at a particular horizontal FOV flight condition.

Data Analysis

Path Control

For each approach task, the objective performance data were analyzed (at a 5 percent level) using a univariate analysis of variance (ANOVA) for each metric. (See refs. 5 and 6.) The independent variables in these ANOVA's were FOV, subjects, and replications.

Touchdown Performance

The trials for the two approach tasks (follow-me, TIFS-only) were pooled together because once the TIFS aircraft had turned onto final, the path for the two tasks was the same. (See fig. 5.) The touchdown performance data were analyzed (at a 5 percent level) using a univariate ANOVA for each metric. The independent variables in these ANOVA's were FOV and subjects.

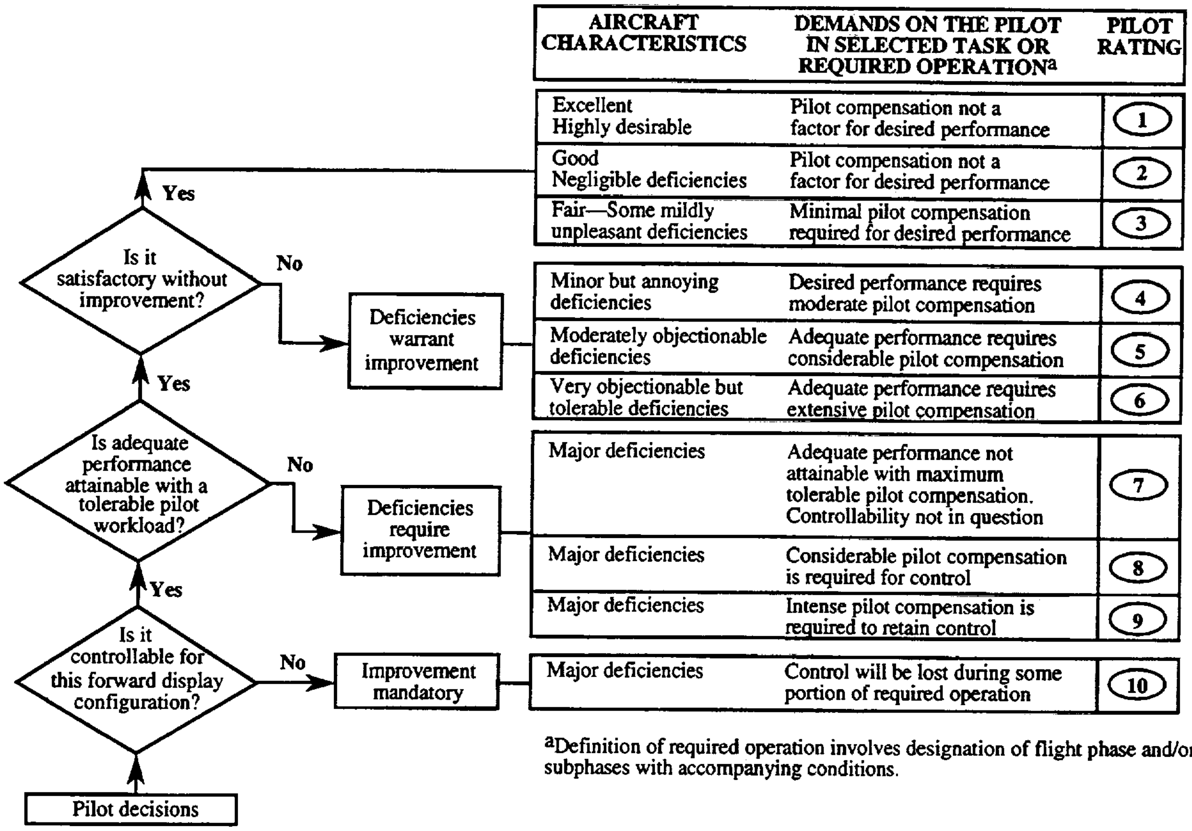


Figure 6. Modified Cooper-Harper rating scale.

Performance standards for the landing

Evaluation segment: **Precision landing from offset**
Start evaluation: 250 ft AGL, final approach speed, descending
End evaluation: Main gear touchdown

Evaluation basis: Evaluate the handling qualities in landing with this forward display configuration. For desired performance, there should be no tendency to pilot induced oscillations or bobble in pitch or roll. There should also be no tendency to float or bounce after touchdown. There should be no tendency for geometry strikes on touchdown.

Performance standards	**Target**	**Desired**	**Adequate**
Landing zone from runway threshold, ft	1250	1000–1500	750–2250
Landing zone from runway centerline, ft	0	± 10	± 27
Maximum touchdown sink rate, ft/sec	≤ 1	≤ 4	≤ 7
Maximum bank angle below 50 ft AGL, deg	0	± 5	± 7
Pilot induced oscillations	None	None	Not divergent
Geometry strikes (tail, engine nacelle, wingtip)	None	None	None

Figure 7. Flight test card for approach tasks.

Results

Objective Data Results

Roll Control Performance

Previous XVS visual display research (ref. 7) performed in the NASA Langley Visual Motion Simulator (VMS) showed significant statistical differences when the maximum bank angle achieved during turns is used as a primary measure. Analyses similar to those performed on the VMS data were performed on the TIFS flight data to see if horizontal FOV had an effect on bank angle during either approach task (follow-me, TIFS-only).

Follow-Me Approach Task. ANOVA analyses on the maximum bank angle achieved during turn one, the turn to base ($F(1,2) = 2.069$, prob. = .287), and turn two, the turn to final ($F(1,3) = .067$, prob. = .813), showed no statistical significance between the 40° and 50° horizontal FOV. (See tables 3 and 4.)

Similar results, showing no FOV effects on the average bank angle attained during turn one ($F(1,2) = 1.338$, prob. = .367), or turn two ($F(1,3) = .207$, prob. = .680), also were found. (See tables 5 and 6.) Furthermore, no statistically significant effects were shown in the subjects or replicates main effects, or in any of the two-way interactions between the three main effects, for either turn on the maximum bank angle achieved or on the average bank angle attained. (Note that the ANOVA analyses for the follow-me approach tasks are missing two cases.)

Table 3. ANOVA Summary on Maximum Bank Angle for Turn to Base for Follow-Me Approach

Source of variation	Sum of squares	Degree of freedom	Mean square	F ratio	Probability
Main effects					
Subject	4.990	2	2.495	1.143	.467
FOV	4.516	1	4.516	2.069	.287
Replication	1.208	2	.604	.277	.783
Two-way interactions					
Subject × FOV	9.012	2	4.506	2.064	.326
Subject × Replications	13.415	4	3.354	1.536	.431
FOV × Replications	.465	2	.232	.106	.904
Residual	4.366	2	2.183		
Total	40.996	15	2.733		

Table 4. ANOVA Summary on Maximum Bank Angle for Turn to Final for Follow-Me Approach

Source of variation	Sum of squares	Degree of freedom	Mean square	F ratio	Probability
Main effects					
Subject	103.194	2	51.597	7.464	.068
FOV	.460	1	.460	.067	.813
Replication	24.589	2	12.294	1.778	.309
Two-way interactions					
Subject × FOV	18.557	2	9.279	1.342	.383
Subject × Replications	17.453	4	4.363	.631	.674
FOV × Replications	47.878	2	23.939	3.463	.166
Residual	20.739	3	6.913		
Total	188.346	16	11.772		

Table 5. ANOVA Summary on Average Bank Angle for Turn to Base for Follow-Me Approach

Source of variation	Sum of squares	Degree of freedom	Mean square	F ratio	Probability
Main effects					
Subject	10.060	2	5.030	2.045	.328
FOV	3.292	1	3.292	1.338	.367
Replication	.048	2	.024	.010	.990
Two-way interactions					
Subject × FOV	1.230	2	.615	.250	.800
Subject × Replications	33.752	4	8.438	3.431	.238
FOV × Replications	9.979	2	4.990	2.029	.330
Residual	4.919	2	2.460		
Total	73.527	15	4.902		

Table 6. ANOVA Summary on Average Bank Angle for Turn to Final for Follow-Me Approach

Source of variation	Sum of squares	Degree of freedom	Mean square	F ratio	Probability
Main effects					
Subject	28.396	2	14.198	2.289	.249
FOV	1.282	1	1.282	.207	.680
Replication	15.656	2	7.828	1.262	.400
Two-way interactions					
Subject × FOV	3.251	2	1.625	.262	.785
Subject × Replications	26.794	4	6.698	1.080	.495
FOV × Replications	5.343	2	2.672	.431	.685
Residual	18.609	3	6.203		
Total	100.597	16	6.287		

TIFS-Only Approach Task. ANOVA analyses on the maximum bank angle achieved during turn one, the turn to base (F(1,4) = .105, prob. = .762), and turn two, the turn to final (F(1,4) = .184, prob. = .690), showed no statistical significance between the 40° and 50° horizontal FOV. (See tables 7 and 8.)

Similar results, showing no FOV effects on the average bank angle attained during turn one (F(1,4) = 012, prob. = .917), or turn two (F(1,4) = 1.110, prob. = .352), also were found. (See tables 9 and 10.) Furthermore, no statistically significant effects were shown in the subjects or replicates main effects, or in any of the two-way interactions between the three main effects, for either turn on the maximum bank angle achieved or on the average bank angle attained.

Table 7. ANOVA Summary on Maximum Bank Angle for Turn to Base for TIFS Approach

Source of variation	Sum of squares	Degree of freedom	Mean square	F ratio	Probability
Main effects					
Subject	32.129	2	16.064	3.024	.158
FOV	.558	1	.558	.105	.762
Replication	.770	2	.385	.073	.931
Two-way interactions					
Subject × FOV	1.046	2	.523	.098	.908
Subject × Replications	6.516	4	1.629	.307	.861
FOV × Replications	.321	2	.160	.030	.970
Residual	21.246	4	5.312		
Total	62.586	17	3.682		

Table 8. ANOVA Summary on Maximum Bank Angle for Turn to Final for TIFS Approach

Source of variation	Sum of squares	Degree of freedom	Mean square	F ratio	Probability
Main effects					
Subject	58.242	2	29.121	3.656	.125
FOV	1.462	1	1.462	.184	.690
Replication	9.666	2	4.833	.607	.589
Two-way interactions					
Subject × FOV	.849	2	.424	.053	.949
Subject × Replications	31.489	4	7.872	.988	.504
FOV × Replications	18.067	2	9.033	1.134	.407
Residual	31.865	4	7.966		
Total	151.640	17	8.920		

Table 9. ANOVA Summary on Average Bank Angle for Turn to Base for TIFS Approach

Source of variation	Sum of squares	Degree of freedom	Mean square	F ratio	Probability
Main effects					
Subject	73.077	2	36.539	4.094	.108
FOV	.110	1	.110	.012	.917
Replication	11.612	2	5.806	.651	.569
Two-way interactions					
Subject × FOV	20.310	2	10.155	1.138	.406
Subject × Replications	48.689	4	12.172	1.364	.385
FOV × Replications	1.297	2	.649	.073	.931
Residual	35.696	4	8.924		
Total	190.792	17	11.223		

Table 10. ANOVA Summary on Average Bank Angle for Turn to Final for TIFS Approach

Source of variation	Sum of squares	Degree of freedom	Mean square	F ratio	Probability
Main effects					
Subject	26.642	2	13.321	3.178	.149
FOV	4.651	1	4.651	1.110	.352
Replication	17.560	2	8.780	2.094	.239
Two-way interactions					
Subject × FOV	2.976	2	1.488	.355	.721
Subject × Replications	21.710	4	5.427	1.295	.404
FOV × Replications	5.600	2	2.800	.668	.562
Residual	16.769	4	4.192		
Total	95.908	17	5.642		

Path Performance

Preliminary analysis of ground track plots indicated that the accuracy of GPS/INS position measuring equipment currently used aboard the TIFS aircraft was insufficient for performance analysis. The present GPS/INS system is only accurate to 100 m. Differential GPS is needed aboard the TIFS aircraft to accurately measure ground track in future XVS flight tests.

Touchdown Performance

The performance values at touchdown for each pilot are listed in table 11. For all but two runs, the subjects performed within the touchdown constraints. For those two runs, the subject landed aft of the adequate landing zone (750–2250 ft) from the runway threshold. The ANOVA's on the touchdown performance measures (table 12) showed no statistically significant differences between the 40°

and 50° horizontal FOV or in any of the interaction terms. Significant differences between the pilots were detected for the threshold altitude performance measure ($F(2,26) = 22.355$, prob. = .000) and for the distance from threshold performance measure ($F(2,26) = 4.597$, prob. = .020).

Table 11. Touchdown Performance Data

Pilot	FOV	Approach condition	Threshold altitude, ft	Distance from threshold, ft	Maximum touchdown sink rate, ft/sec
1	40	TIFS-only	Not available	Not available	3.1
1	40	TIFS-only	28	1770	4.8
1	40	TIFS-only	26	1190	3.8
1	50	TIFS-only	32	1050	6.3
1	50	TIFS-only	39	1310	3.8
1	50	TIFS-only	36	1360	3.2
2	40	TIFS-only	35	1340	3.7
2[a]	40	TIFS-only	19	1100	3.6
2	40	TIFS-only	Skipped	Skipped	Skipped
2	50	TIFS-only	20	1040	3.1
2	50	TIFS-only	20	1110	3.4
2	50	TIFS-only	26	860	2.8
3	40	TIFS-only	46	1910	3.6
3	40	TIFS-only	49	1970	5.1
3	40	TIFS-only	43	1370	3.5
3	50	TIFS-only	Not available	Not available	3.1
3	50	TIFS-only	Not available	Not available	4.5
3	50	TIFS-only	46	1860	4.6
1	40	Follow-me	21	1700	3.9
1	40	Follow-me	16	1800	3.9
1	40	Follow-me	21	1330	5.1
1	50	Follow-me	36	1220	5.2
1	50	Follow-me	22	1680	2.4
1	50	Follow-me	17	1460	2.0
2[a]	40	Follow-me	23	1140	2.2
2	40	Follow-me	21	540	3.7
2	40	Follow-me	33	2250	4.0
2	50	Follow-me	41	1760	4.3
2	50	Follow-me	27	900	5.5
2	50	Follow-me	34	1470	2.0
3	40	Follow-me	48	2310	5.0
3	40	Follow-me	48	1780	5.2
3	40	Follow-me	42	2330	5.5
3	50	Follow-me	39	1500	3.0
3	50	Follow-me	44	1010	5.3
3	50	Follow-me	37	1810	5.1

[a]Distance from threshold is an estimate because threshold marker was not called out at proper time.

Table 12. Analysis of Variance Results for Touchdown Performance Measures

Factor	Degrees of freedom	F Ratio	Significance of touchdown performance measures—
Threshold altitude			
Pilots	2	22.355	.000
Horizontal FOV	1	.551	.465
Pilots × Horizontal FOV	2	2.284	.122
Error	26		
Total (four cases missing)	31		
Distance from threshold			
Pilots	2	4.597	.020
Horizontal FOV	1	2.870	.102
Pilots × Horizontal FOV	2	.438	.650
Error	26		
Total (four cases missing)	31		
Maximum touchdown sink rate			
Pilots	2	2.300	.118
Horizontal FOV	1	.282	.600
Pilots × Horizontal FOV	2	.138	.872
Error	29		
Total (one case missing)	34		

Subjective Results

Landing Performance

Modified C-H ratings were assigned by each pilot for the landing phase of flight for both flying tasks and both FOV's. (See table 13.) Note that each rating is based on a series of three runs, except in the 40° horizontal FOV TIFS-only subset because pilot 2 performed only two of the three runs. As mentioned earlier, fuel limitations of the TIFS aircraft precluded this run from occurring during the 2 days of flight testing.

Table 13. Modified Cooper-Harper Ratings for Both Flying Tasks and Both FOV's

	Modified Cooper-Harper rating		
Run type	Pilot 1	Pilot 2	Pilot 3
40° horizontal FOV follow-me	4	4.5	5
50° horizontal FOV follow-me	4	4.5	5
40° horizontal FOV TIFS-only	4	4	5
50° horizontal FOV TIFS-only	4	4	5

The modified C-H ratings indicated that either FOV provided adequate performance for both flying tasks. According to EP opinions, these ratings are more applicable to rating the control law ($\dot{\gamma}V$) used in the flight test than rating the forward display configuration.

Touchdown Performance

EP opinion was that inboard FOV had no effect on landing performance because all the information needed by the pilots to land is located within the 20° FOV of the TIFS F/A-18 HUD.

Questionnaire Results

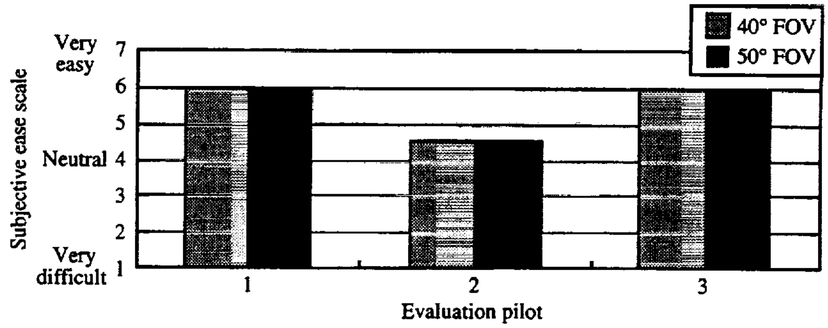
Each EP completed a questionnaire and expressed his opinion on the ease of usability of the two FOV's for the two flying tasks. (See appendix C and the section on Performance Metrics.) Paired-*t* tests (refs. 6 and 7) were used to analyze the subjective ratings and no significant statistical differences for the 40° and 50° horizontal FOV's were found.

Unlike the rating results, EP comments on the questionnaire indicated that horizontal FOV effects were seen during turns (either when following the lead aircraft or when using geographical references) and during acquisition of the runway after turn to final. In these cases, the 50° FOV was preferred over the 40° FOV because the objects (lead aircraft, runway) could be acquired more quickly with the larger FOV. As illustrated in figure 8, comments indicate that straight and level flight and final approach and landing were not affected by horizontal FOV. Figure 8 also shows that pilots preferred the larger horizontal FOV during the entire landing approach (base-downwind-final) for both flying tasks.

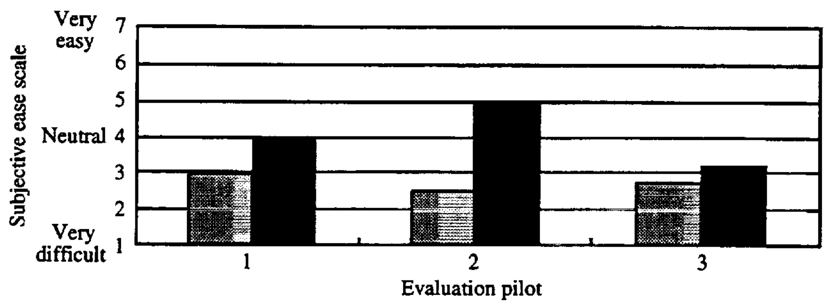
The 10-knot crosswind on final was not a horizontal FOV issue because, during landing, the runway was in sight for both the 40° and 50° horizontal FOV forward display configurations. The pilots commented that the HUD is compelling in attitude control during landing because it provides all the information needed by the pilots to land the aircraft.

TIFS Capabilities

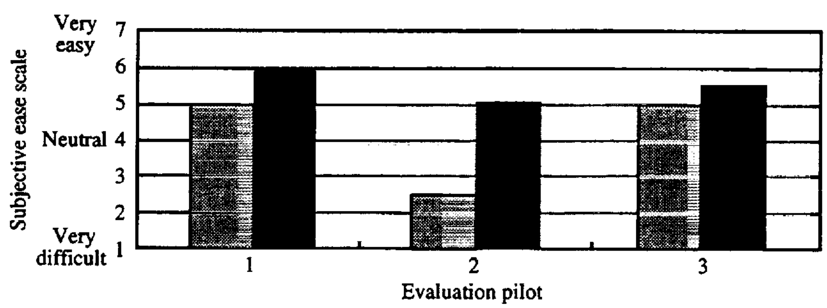
Flight time aboard the TIFS aircraft yielded some interesting insight into the capabilities and limitations of this in-flight simulator. To have adequate model following, the simulation flights should be flown in the smoothest atmospheric conditions possible (minimal turbulence). Another environmental constraint is that the TIFS aircraft must fly in VFR conditions. The aircraft is only able to augment the natural crosswind by ±5 knots, not ±15 knots as the researchers originally thought. This limitation of the TIFS aircraft is due to the aft position of the center of rotation of the HSCT model. Being so far back, this center of rotation uses much of the side force capability of the TIFS aircraft, leaving only enough motion to produce ±5 knots of augmented crosswind. The crosswind corrections are not automatically processed throughout the entire simulation, but are commanded manually by Calspan's onboard engineer. Also, aggressive roll inputs (large delta roll in a short amount of time) by the EP will trip off the simulation, resulting in a takeover condition by the safety pilot. This roll input limitation of the TIFS test vehicle may cause pilots to alter their flying patterns, which could affect control performance.



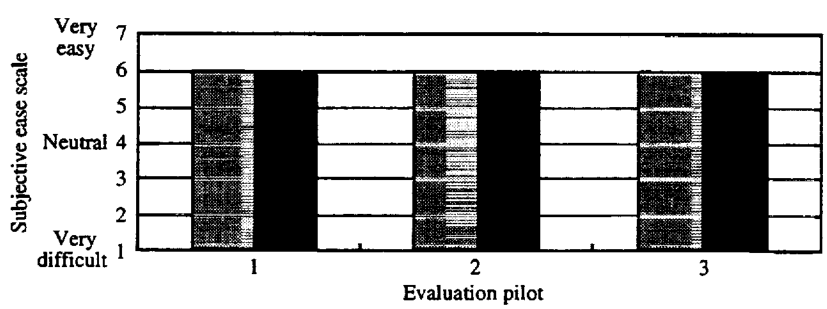
(a) Usability of forward display configuration for maintaining path on final with a left crosswind.



(b) Usability of forward display configuration for following the Be-200 general aviation aircraft.



(c) Usability of forward display configuration for flying entire landing approach.



(d) Usability of forward display configuration for flying straight and level on downwind-base.

Figure 8. Subjective results on ease of usability of two forward display configurations flown at Niagara Falls Airport.

As mentioned previously, differential GPS is needed aboard the TIFS aircraft for future XVS flight tests to accurately measure ground track. The follow-me task was difficult to fly and analyze without differntial GPS for each aircraft since the initial conditions and ground track were different on each approach. (It was desired to use the ground track of the lead aircraft as the performance reference for the TIFS ground track.)

Concluding Remarks

An experiment was performed with Calspan's Total In-Flight Simulator (TIFS) aircraft to investigate the effects of inboard horizontal field of view (FOV) display limitations on pilot path control and to learn about the TIFS capabilities and limitations for possible use in future eXternal Visibility System (XVS) flight tests. Both objective and subjective data were collected to determine possible inboard FOV effects on pilot path control and landing performance.

No statistical differences between the 40° and 50° horizontal FOV's were found in the objective data analyzed. The data analyzed were the maximum bank angle achieved in both turns, the average bank angle attained during both turns, and the touchdown performance measures (threshold altitude, distance from threshold, and maximum touchdown sink rate). There were no statistical differences between the FOV conditions as measured by modified Cooper-Harper ratings. However, subjective results indicated that the 50° FOV was preferred over the 40° FOV for following the Be-200 general aviation aircraft, flying the entire landing approach (downwind-base-final), and acquiring the runway and/or target after rolling out on final approach. Pilot comments indicated that straight and level flight and final approach and landing were not affected by horizontal FOV.

The global positioning system (GPS)/inertial navigation system (INS) equipment aboard the TIFS aircraft was insufficient for evaluating ground track and landing performance because the GPS/INS system was only accurate to 100 m. The experimental follow-me flying task was difficult to set up and measure without differential GPS for each aircraft because the initial conditions and ground track were different for each approach. Differential GPS is needed aboard the aircraft to accurately measure ground track in future XVS flight tests. For all approaches, the 10-knot crosswind on final was not an FOV issue because the crab angle of the aircraft was not enough to obscure the pilot's view of the runway for either the 40° or 50° horizontal FOV. In fact, all information needed by the pilots to land is located within the 20° FOV of the TIFS F/A-18 heads-up display, available for all flight conditions. Also, aggressive roll inputs (large delta roll in a short amount of time) by the evaluation pilot will trip off the simulation, resulting in a takeover condition by the safety pilot. This roll input limitation of the TIFS test vehicle may cause pilots to alter their flying patterns, which could affect control performance. According to subject opinion, the modified Cooper-Harper ratings were more applicable to rating the control law ($\dot{\gamma}V$) used in the flight test than rating the forward display configuration. The development of an appropriate evaluation instrument for comparing and assessing display concepts would be useful for future XVS research experiments.

The successful completion of this flight test provided valuable insight regarding not only the issue of horizontal inboard FOV, but also about the TIFS in-flight simulation capabilities and limitations for possible use in future flight tests by the XVS element of the High-Speed Research Flight Deck Systems program.

NASA Langley Research Center
Hampton, VA 23681-2199
August 3, 1998

Appendix A

Landing Vision Requirements in ARP4101/2

Landing Vision

The view angle forward and down shall be sufficient to allow the pilot to see a length of approach and/or touch down zone lights which would be covered in 3 sec at landing approach speed when the aircraft is

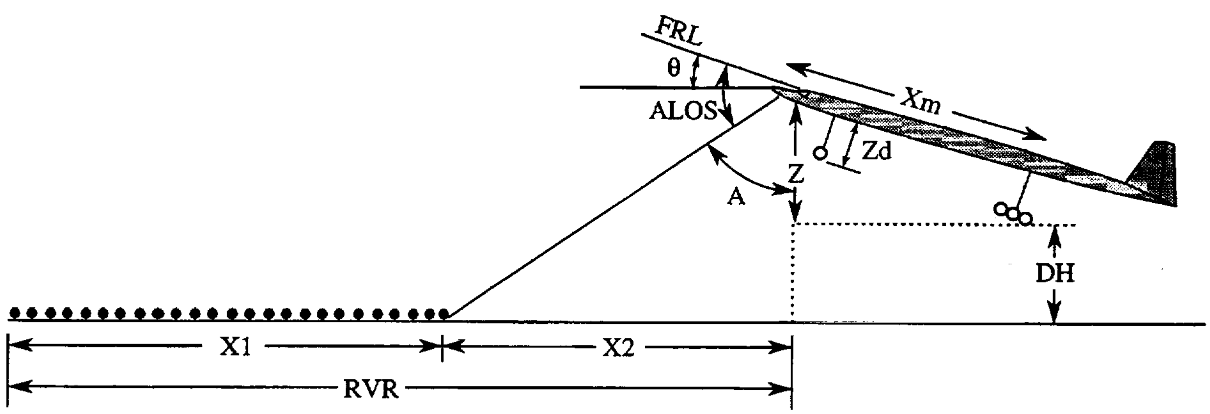
On a 2-1/2° glide slope

At a decision height that places the lowest part of the aircraft at 30.6 m (100 ft) above the touch-down zone extended horizontally

Yawing to the left to compensate for 10-knot crosswind

Loaded to the most critical weight and center of gravity

Making the approach with 366 m (1200 ft) RVR



Abbreviations

A angle between vertical axis beneath PERP and nearest light which must be visible, deg; $\arctan \dfrac{X2}{Z + DH}$

ALOS angle between FRL and nearest light which must be visible, deg; $\theta + 90 - A$

AOA aircraft approach angle of attack, deg

DH 100 ft, as per ARP-4101/2

DT lights transit time, 3 sec, as per ARP-4101/2

FRL fuselage reference line

GS glide slope, 2.5 deg, as per ARP-4101/2

MLG main landing gear

PERP pilot eye reference point

RVR 1200 ft runway visual range, as per ARP-4101/2

V approach speed, knots true airspeed

X1 length of lights which must be visible, ft; $1.688 \times V \times DT$

X2 RVR – X1

Xm distance along aircraft x-axis between MLG and PERP, ft

Z vertical (Earth referenced) distance from MLG to PERP, ft; $Xm \times \sin\theta + Zd \times \cos\theta$

Zd distance along aircraft z-axis between MLG and PERP, ft

θ aircraft pitch attitude, deg; AOA – GS

Source: Reference 1.

Appendix B

Data Elements Recorded for TIFS Aircraft

altitude rate, $\dot{h}$, ft/sec

angle of attack, α, deg

bank angle, ϕ, deg

calibrated airspeed, V_{cas}, ft/sec

dynamic pressure, $\bar{q}$, lb/ft^2

flight condition (run number, date, time)

flight path angle, γ, deg

glide slope error, dots

ground speed, V_{gr}, ft/sec

heading angle, deg

inertial position x, ft

inertial position y, ft

inertial position z, ft

inertial velocity (from INS), ft/sec

landing gear, lgear, 0(up) or 1(down)

lateral acceleration, A_y, g units

lateral stick force, lb

lateral stick position, in.

left aileron, l_{ail}, deg

localizer error, dots

longitudinal acceleration, deg/sec^2

longitudinal stick force, lb

longitudinal stick position, in.

normal acceleration, A_n, g units

other surface positions, deg

pitch angle, θ, deg

pitch rate, q, deg/sec

pressure altitude, h, ft

radar altitude above ground, h, ft

right aileron, r_{ail}, deg

roll rate, p, deg/sec

sideslip angle, β, deg

throttle command, percent

throttle position, percent

true airspeed, V, ft/sec

yaw angle, ψ, deg

yaw rate, r, deg/sec

Appendix C

Sample Questionnaire

Pilot # _______ **Scenario 1 / 2 HFOV 40° / 50° Date:** ________

Horizontal Field of View (HFOV) Questionnaire

Based on the forward display configuration that you have just seen (either 40° or 50° horizontal FOV), please complete the following evaluation, placing a "**40**" or "**50**" on the scale corresponding to your estimate of effort required to use this display configuration.

After each series of flying tasks, this same questionnaire will be used for both the 40° HFOV and 50° HFOV forward display configurations. **The intent of this questionnaire is to identify possible effects on pilot path control when increasing the inboard horizontal field of view of the forward display by 10 degrees.**

The following are **EXAMPLES** of how to complete the questionnaire:

Example 1: Evaluate the ease of flying the inertial ground track by the out-the-window cues.

1	2	3	4	5	6	7
		50 **40**				
very hard	somewhat hard		neutral	somewhat easy		very easy

Example 2: Evaluate your ability to achieve the proper track angle after rolling out of a level, right-hand turn.

1	2	3	4	5	6	7
			40	**50**		
very hard	somewhat hard		neutral	somewhat easy		very easy

QUESTIONS:

1. Evaluate your ability to

    a. fly **straight and level** on the **downwind leg** of the flight.

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

* b. **initiate a level turn** from downwind to base.

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

c. **roll out of the turn** onto the base leg of the flight.

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

* d. **observe track angle errors and decide on needed corrections** to achieve a level, right-hand turn onto base.

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

* e. **achieve lateral ground track alignment** after rolling out of a level, right-hand turn onto base.

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

Comments for 40° HFOV: ____

____

____

____

____

Comments for 40° HFOV: ____

____

____

____

____

2. Evaluate your ability to

a. fly **straight and level** on the **base leg** of the flight.

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

* b. **initiate a level turn** from base to the 300-ft lateral offset on final.

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

* c. **roll out of the turn** onto the 300-ft lateral offset on final approach.

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

* d. **observe track angle errors and decide on needed corrections** to achieve a level, right-hand turn onto the 300-ft lateral offset on final.

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

* e. **achieve lateral ground track alignment** after rolling out of a level, right-hand turn onto the 300-ft lateral offset on final.

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

Comments for 40° HFOV: ______________________________

____

____

____

____

Comments for 50° HFOV: ____

____

____

____

____

3. Evaluate your ability to

a. fly **approach** on the **300-ft lateral offset on final.**

1	2	3	4	5	6	7
very hard		somewhat hard	neutral	somewhat easy		very easy

b. **initiate a step maneuver** from the 300-ft lateral offset to align with the runway.

1	2	3	4	5	6	7
very hard		somewhat hard	neutral	somewhat easy		very easy

c. **roll out of the step maneuver** to align with the runway.

1	2	3	4	5	6	7
very hard		somewhat hard	neutral	somewhat easy		very easy

d. **observe track angle errors and decide on needed corrections** to achieve the step maneuver and align with the runway.

1	2	3	4	5	6	7
very hard		somewhat hard	neutral	somewhat easy		very easy

e. **achieve lateral ground track alignment** after rolling out of the step maneuver.

1	2	3	4	5	6	7
very hard		somewhat hard	neutral	somewhat easy		very easy

Comments for 40° HFOV: ____

____

____

____

Comments for 50° HFOV: ____

____

____

____

*4. Usability of this configuration for **maintaining path on final with a left crosswind.**

|________|________|________|________|________|________|________|

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

Comments for 40° HFOV: ____

____

____

____

____

Comments for 50° HFOV: ____

____

____

____

____

*5. Usability of this configuration for **following the Beechcraft Be-80 (or equivalent) general aviation aircraft.**

|________|________|________|________|________|________|________|

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

Comments for 40° HFOV: ____

____

____

____

____

Comments for 50° HFOV: ____

____

____

____

____

*6. Usability of this configuration for **landing approach** (entire time evaluation pilot has control of the aircraft).

1	2	3	4	5	6	7
very hard		somewhat hard	neutral	somewhat easy		very easy

Comments for 40° HFOV: ____

____

____

____

____

Comments for 50° HFOV: ____

____

____

____

____

7. Usability of this configuration for **landing flare**.

1	2	3	4	5	6	7
very hard		somewhat hard	neutral	somewhat easy		very easy

Comments for 40° HFOV: ____

Comments for 50° HFOV: ____

*8. Evaluate the ease of **flying the inertial ground track by the out-the-window cues.**

1	2	3	4	5	6	7
very hard	somewhat hard		neutral	somewhat easy		very easy

Comments for 40° HFOV: ____

Comments for 50° HFOV: ____

GENERAL COMMENTS:

Usability of this configuration for **roll control performance.**

Comments for 40° HFOV: ______________________________

Comments for 50° HFOV: ______________________________

Usability of this configuration for **scanning for traffic.**

Comments for 40° HFOV: ______________________________

Comments for 50° HFOV: ______________________________

When would you expect problems with this display configuration?

Comments for 40° HFOV: ______________________________

Comments for 50° HFOV: ______________________________

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13. ABSTRACT *(Maximum 200 words)*

A flight test was conducted aboard Calspan's Total In-Flight Simulator (TIFS) aircraft by researchers within the eXternal Visibility System (XVS) element of the High-Speed Research program. The purpose was to investigate the effects of inboard horizontal field of view (FOV) display limitations on pilot path control and to learn about the TIFS capabilities and limitations for possible use in future XVS flight tests. The TIFS cockpit windows were masked to represent the front XVS display area and the High-Speed Civil Transport side windows, as viewed by the pilot. Masking limited the forward FOV to 40° horizontal and 50° vertical for the basic flight condition, with an increase of 10° horizontal in the inboard direction for the increased FOV flight condition. Two right-hand approach tasks (base-downwind-final) with a left crosswind on final were performed by three pilots using visual flight rules at Niagara Falls Airport. Each of the two tasks had three replicates for both horizontal FOV conditions, resulting in twelve approaches per test subject. Limited objective data showed that an increase of inboard FOV had no effect (deficiences in objective data measurement capabilities were noted). However, subjective results showed that a 50° FOV was preferred over the 40° FOV.

14. SUBJECT TERMS	15. NUMBER OF PAGES
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